Integrated Coastal Modeling

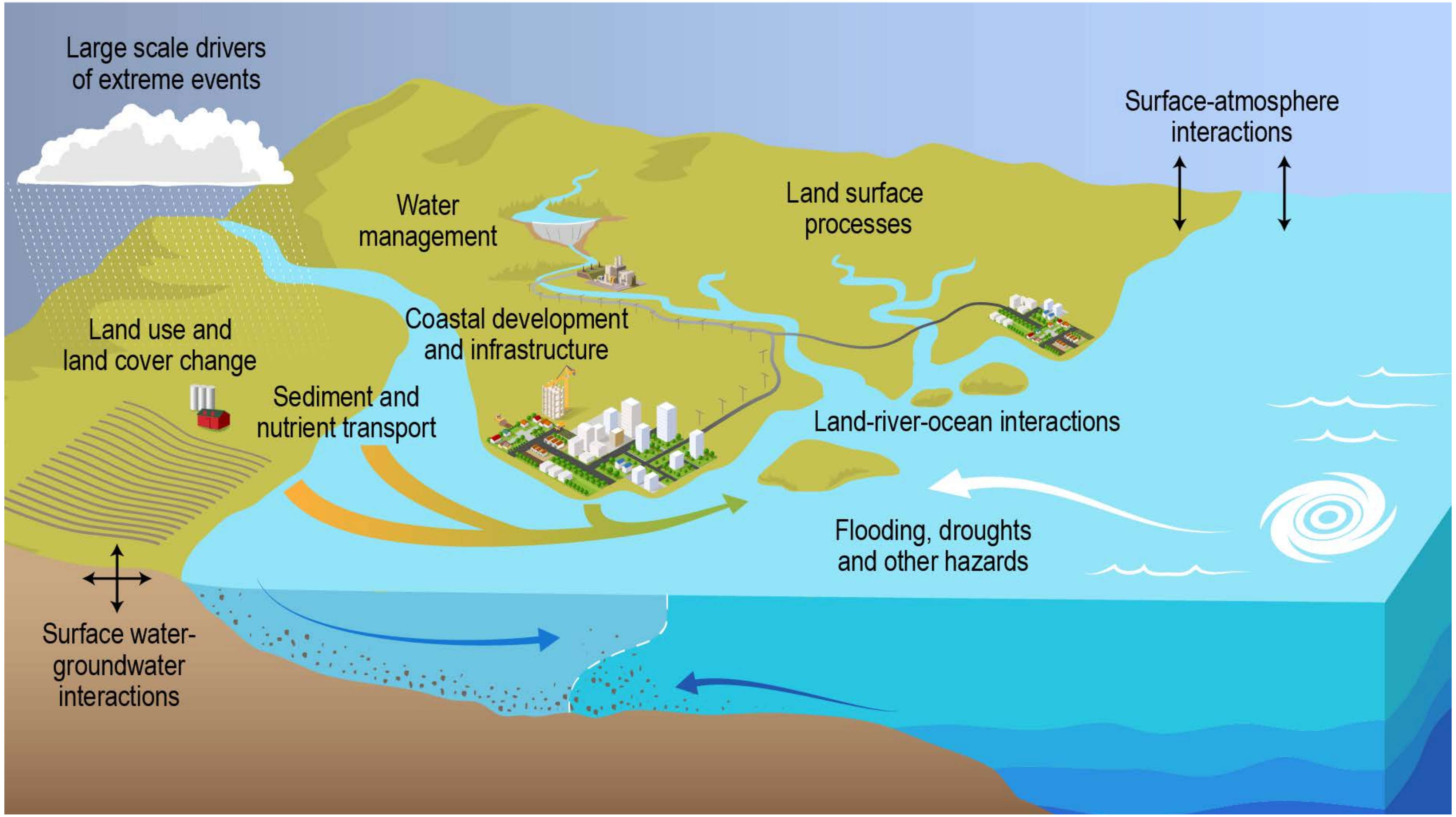
Elizabeth Hunke

PI, ESMD program area

PNNL is operated by Battelle for the U.S. Department of Energy

ICoM is funded by multiple programs in the Earth and Environmental Systems Sciences Division of DOE's Office of Science

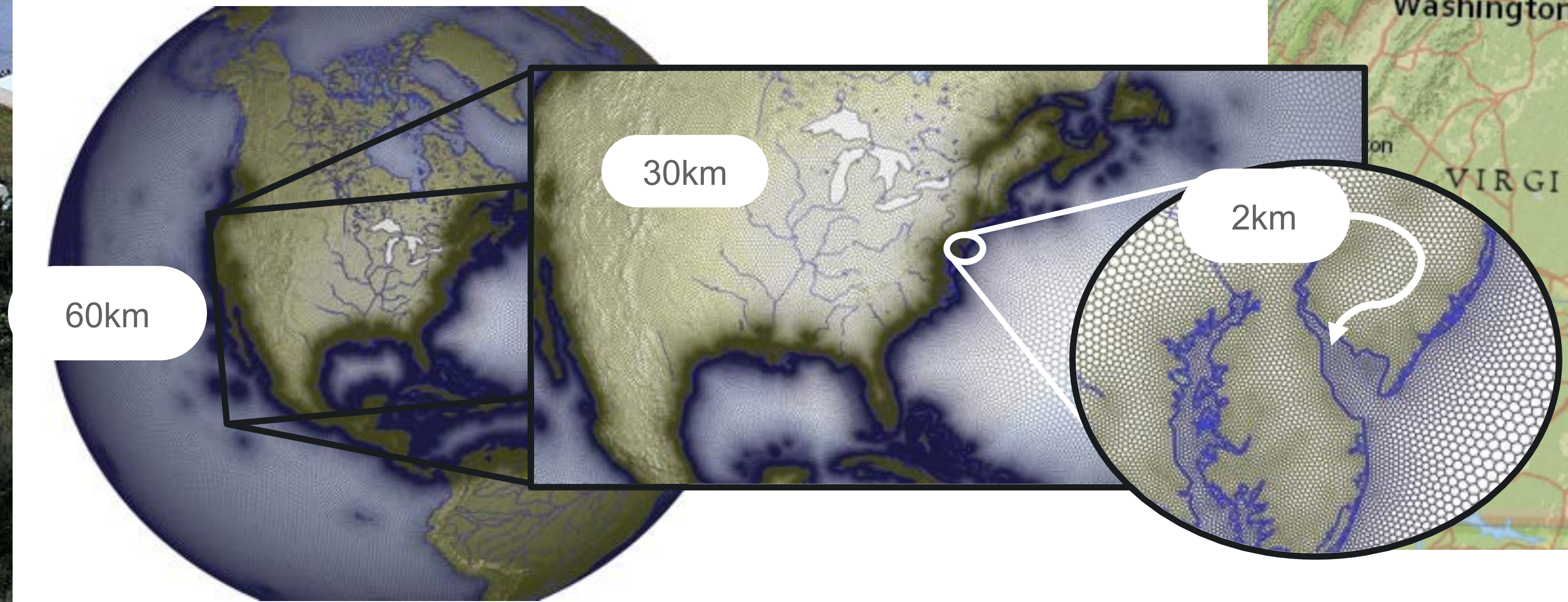
ICoM focuses on key processes and uncertainties



Our long-term vision is to deliver a robust predictive understanding of coastal evolution that accounts for the complex, multiscale interactions among physical, biological, and human systems

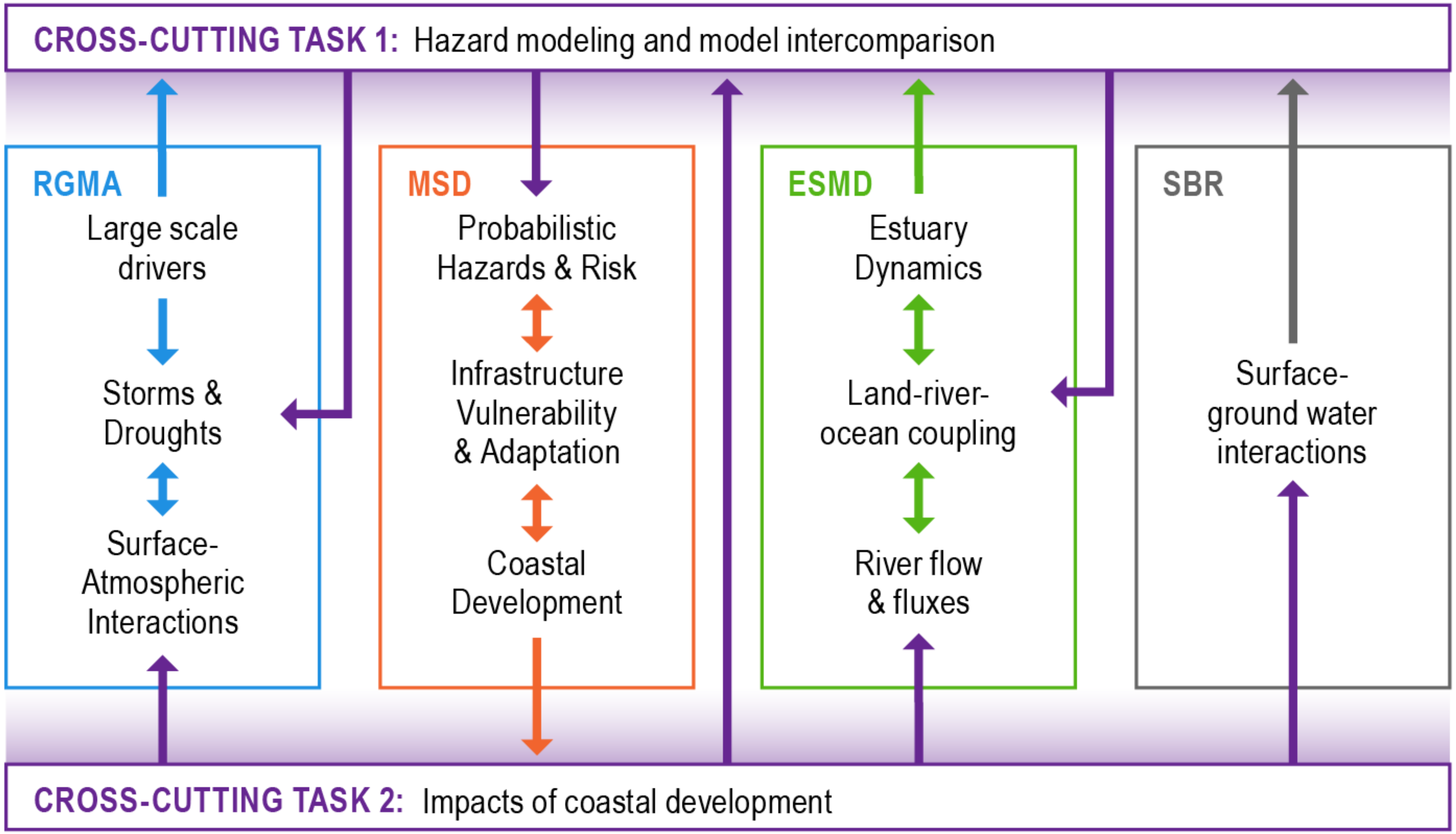
Mid-Atlantic Study Region

- Exposed to many different stresses and extremes
- Coastal modeling integrated into E3SM development
  - Global-to-coastal regional mesh refinement



Accounting for complex, multiscale interactions among physical, biological, and human systems

ICoM's cross-cutting research tasks leverage and inform activities in each of the programmatic research areas



Extending E3SM to improve the representation of human-land-river-ocean interactions

Earth System Model Development (ESMD) Program Area

ESMD PI
Elizabeth Hunke

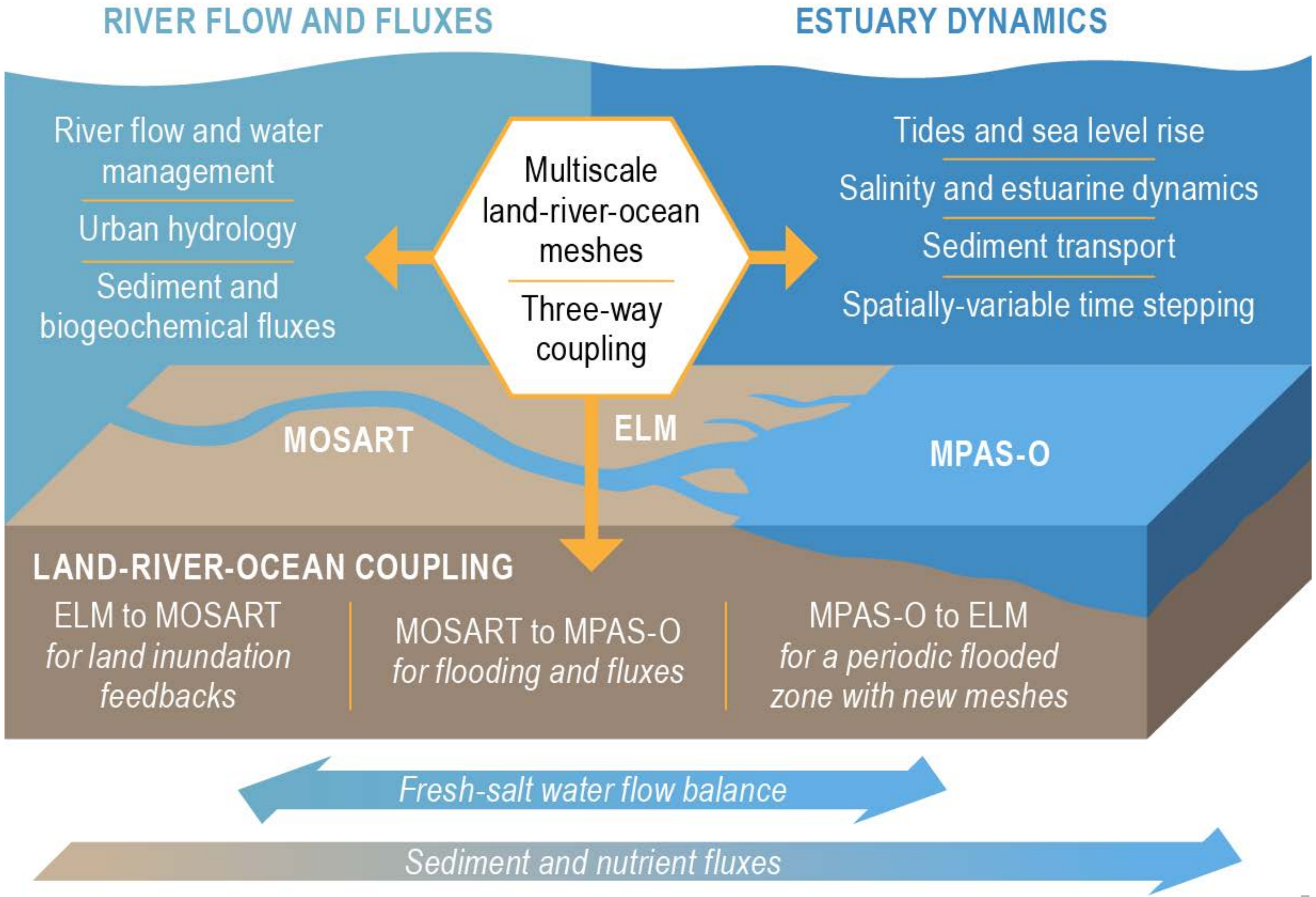
Task Leads

Zeli Tan

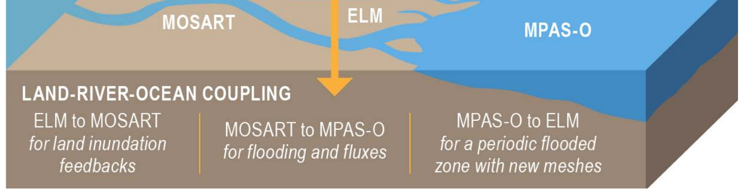
Tian Zhou

Gautam Bisht

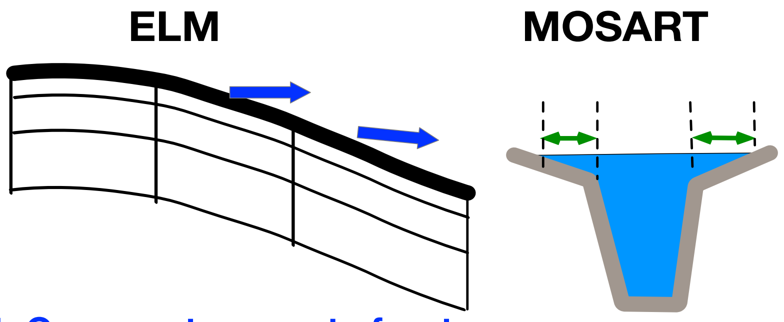
… and
numerical experiments



Land-River-Ocean Coupling

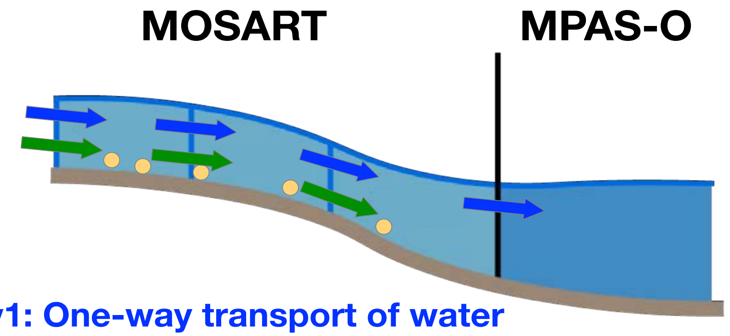


Ongoing E3SM developments



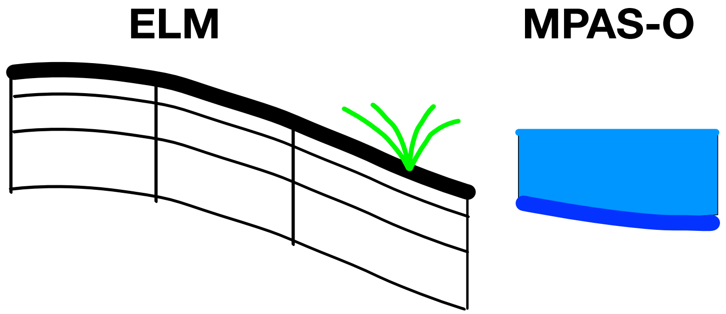
E3SM v1: One-way transport of water

E3SM v2*: Floodplain inundation estimated by MOSART



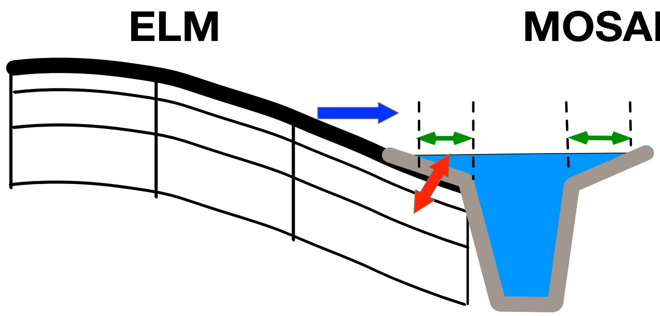
E3SM v1: One-way transport of water

E3SM v2*: Heat & sediment transport in MOSART

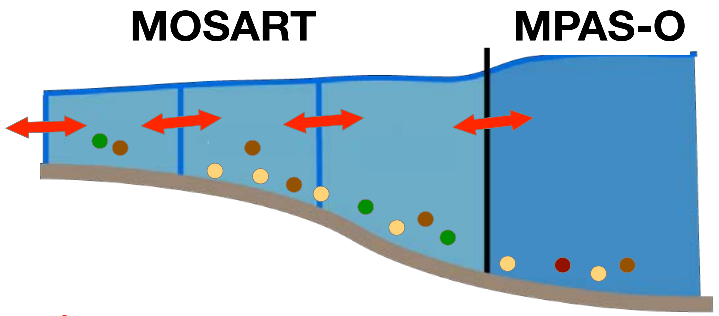


E3SM v1 and v2*: Time invariant land/ocean fraction with no coupling between land and ocean components

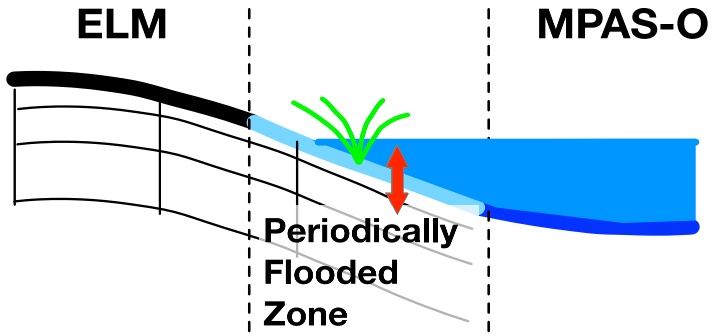
ICoM proposed developments



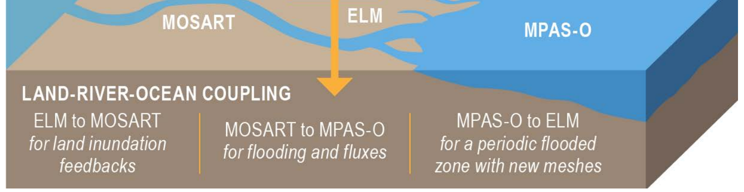
E3SM v3/v4: Floodplain inundation will alter hydrologic, thermal, and ecological processes in ELM



E3SM v3/v4: Two-way transport of water, heat, sediment, and biogeochemistry



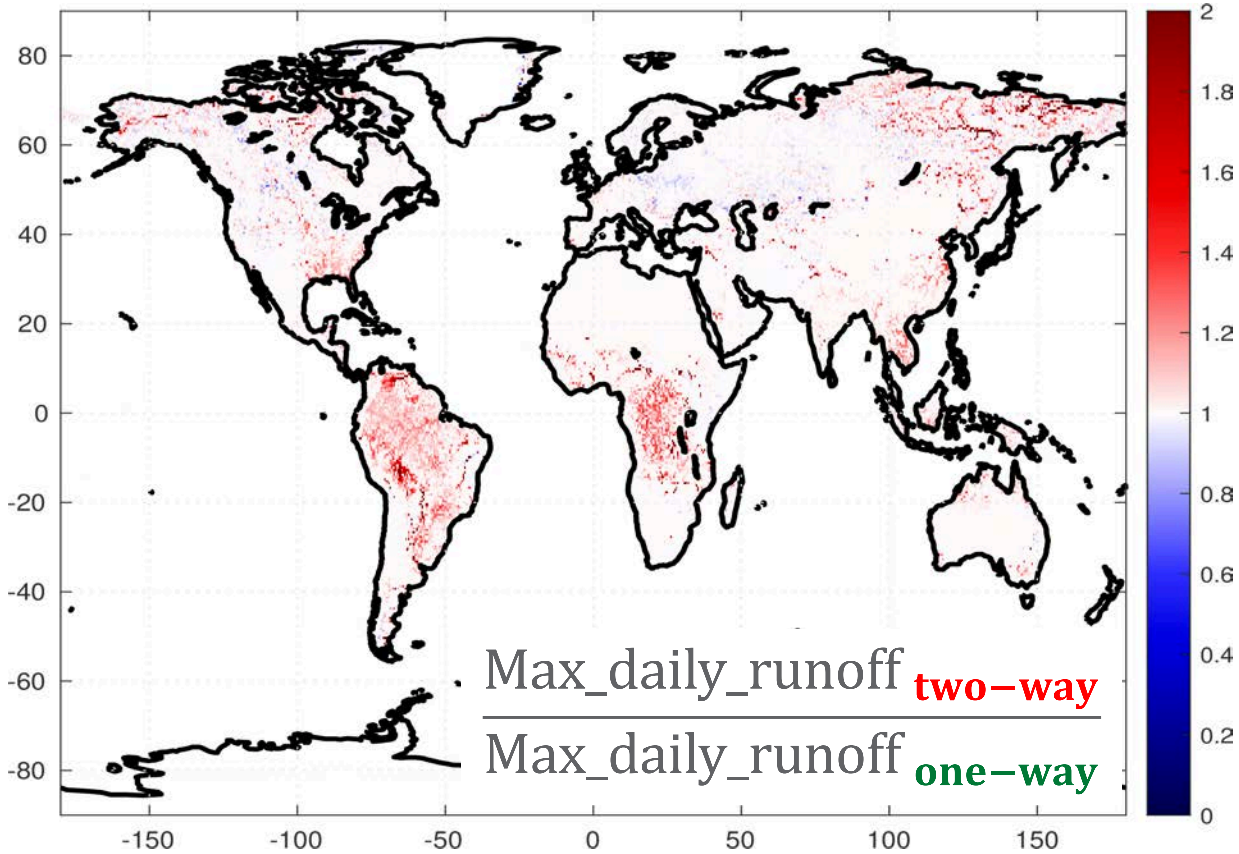
E3SM v3/v4: Dynamic land/ocean fraction with two-way exchange of water, heat, and biogeochemistry



Land-River Coupling

Model configuration

- Resolution: 0.5°×0.5°
- COMPSET: IELM (ELM+MOSART)
- QIAN atmospheric forcing
- Time period: 1951-1970
  - First 15 years: "spin up"
  - Last 5 years: comparison
- Configurations
  - Land-river one-way coupled
  - Land-river two-way coupled



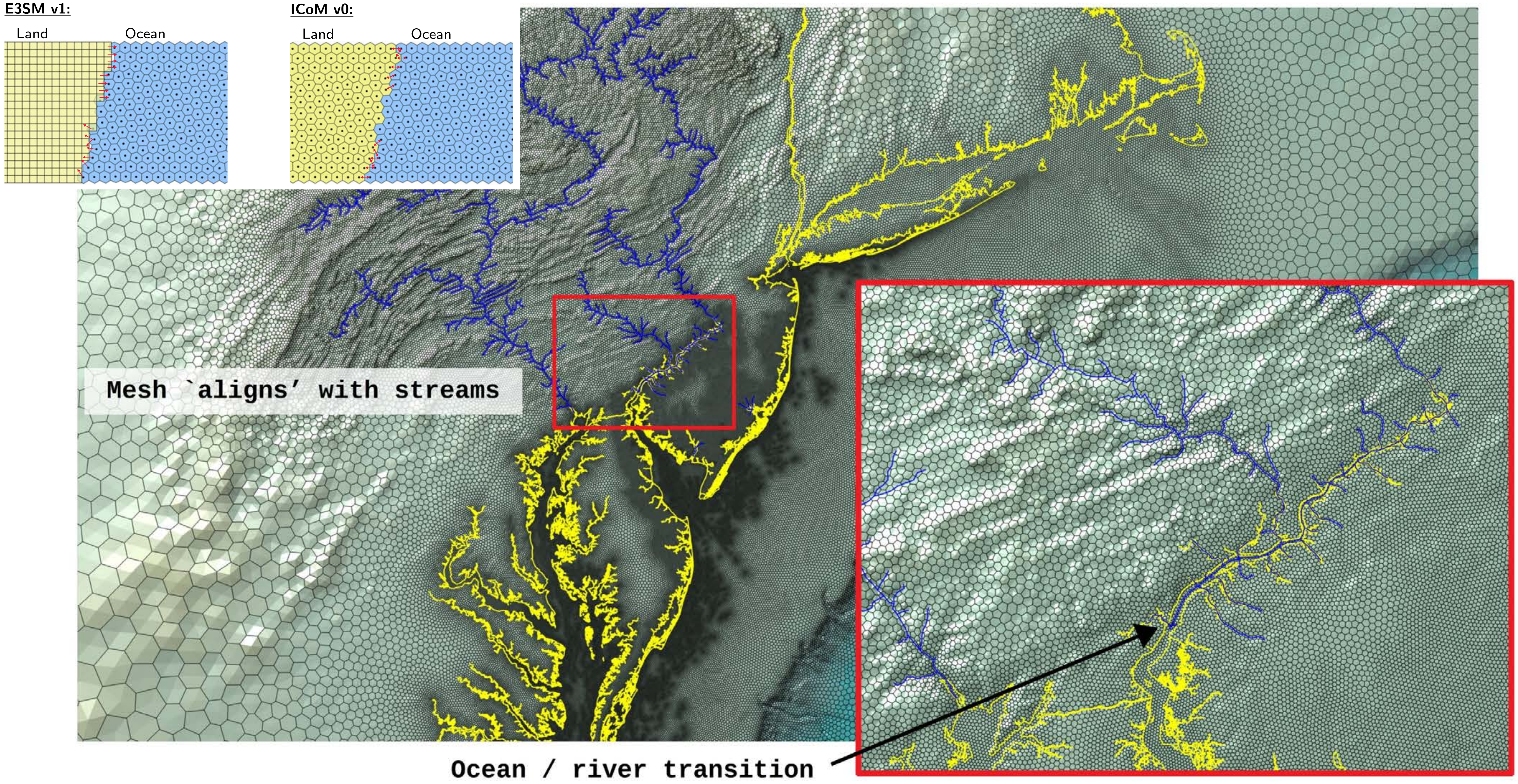
Compared to one-way coupled model, in the two-way coupled model:

- **87%** cells show a change in maximum peak annual runoff or fraction of inundated land grid cell
- **13%** cells have an increase of peak annual runoff at least 5%
- **2%** cells have a decrease of peak annual runoff at least 5%

Gautam Bisht

Poster: *Land river two-way coupling development in E3SM* (Xu, PS2-Land_River_&_Energy)
Poster: *MOSART-Urban: a semi-distributed regional urban flood modeling framework* (Li, PS2)

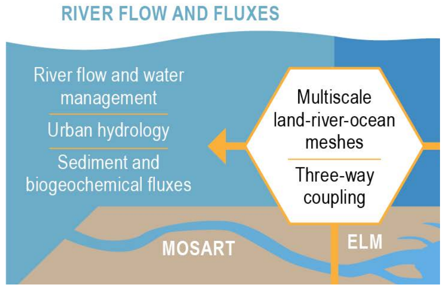
Overcoming land-river-ocean coupling challenges



Poster: *'Unified' ocean/land/river modelling using compatible unstructured meshes* (PS1-Ocean_Coastal)

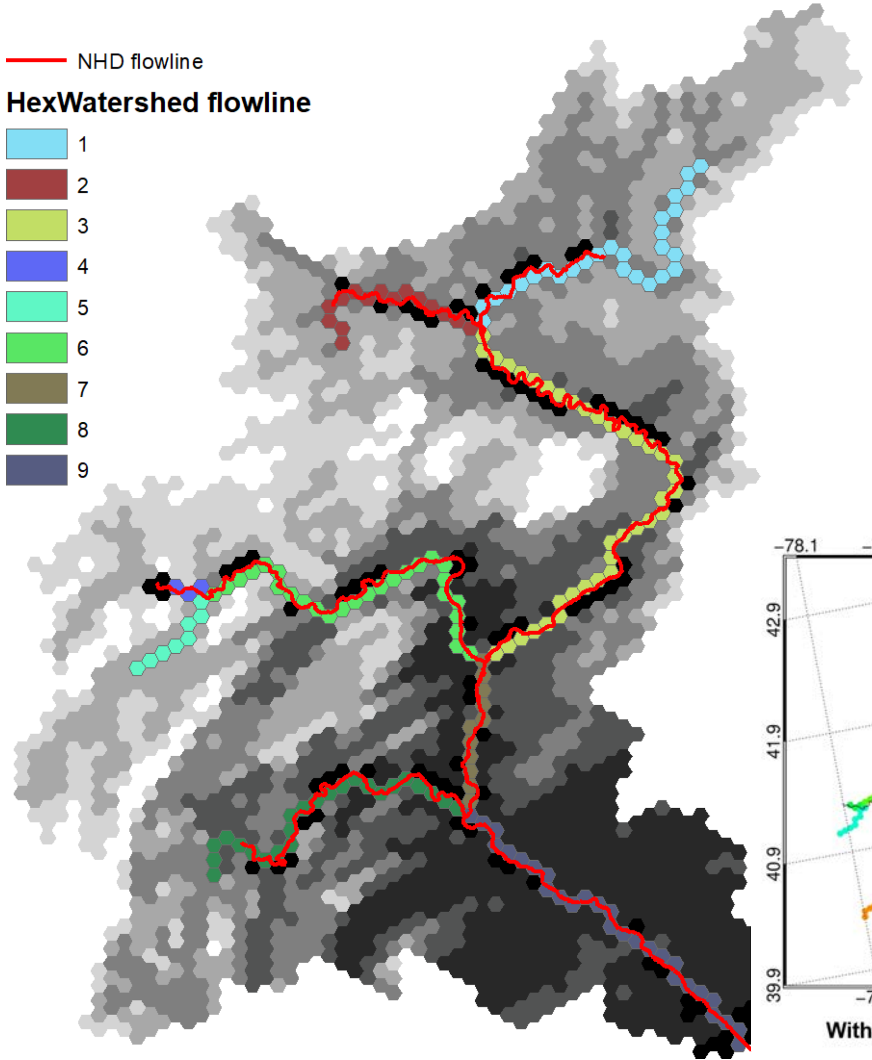
Darren Engwirda

Flow Routing on an unstructured mesh



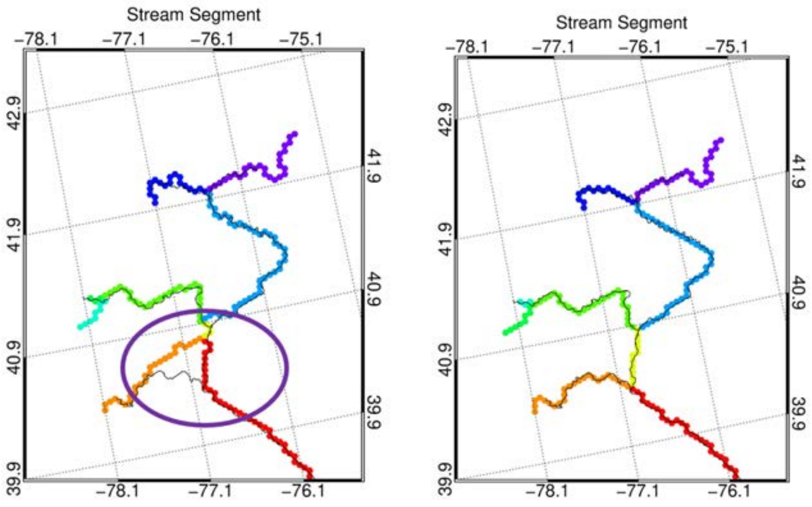
The performance of watershed delineation is subject to the spatial resolution of underlying Digital Elevation Model (DEM). Therefore, a **"stream burning"** capability was added to the HexWatershed to maintain **flow direction** even at coarse spatial resolutions.

HexWatershed stream segment
Resolution: 5km



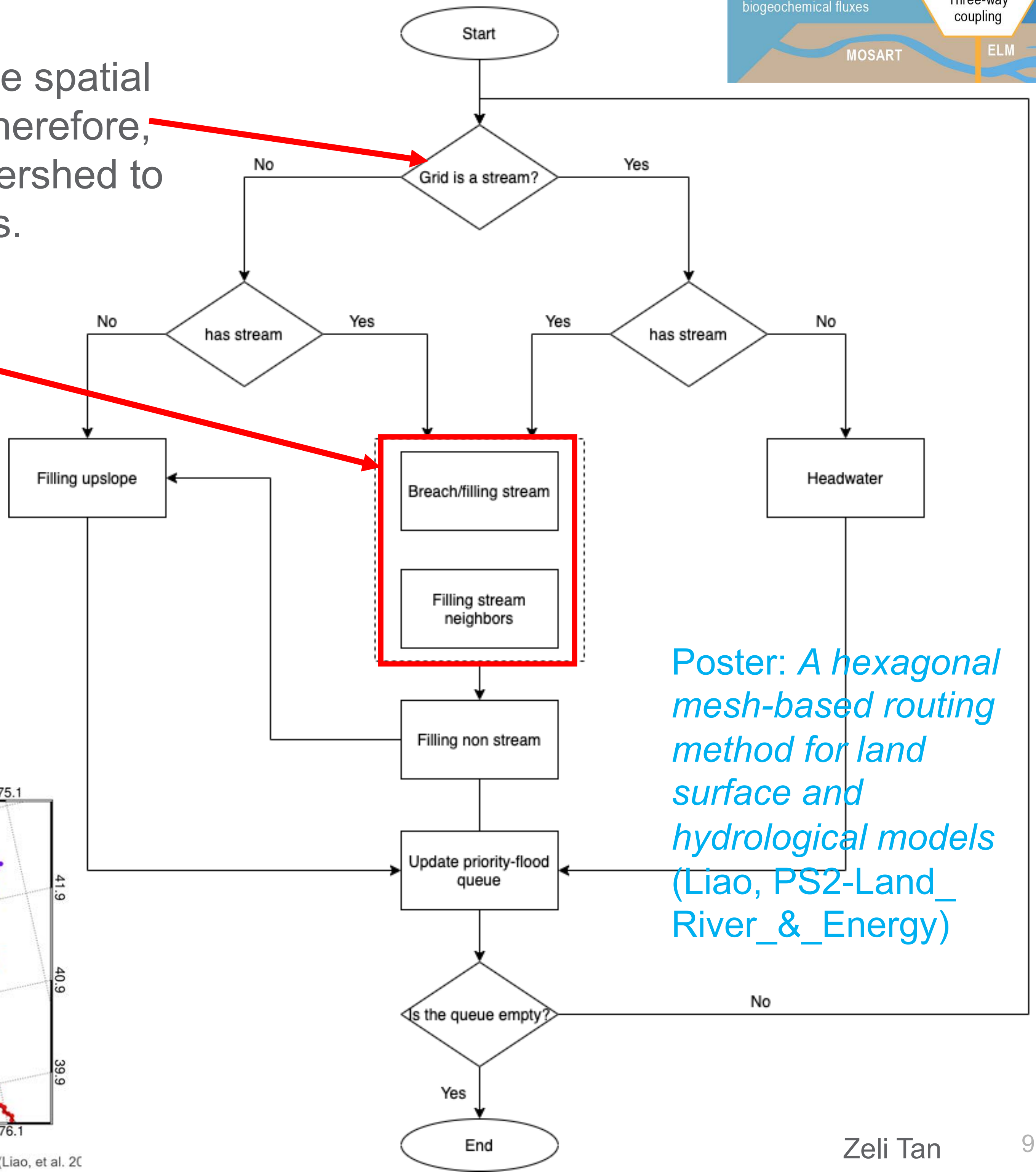
A hybrid **breaching-filling** algorithm is used minimize the modification to DEM.

Provide support for MPAS mesh and VTK visualization.



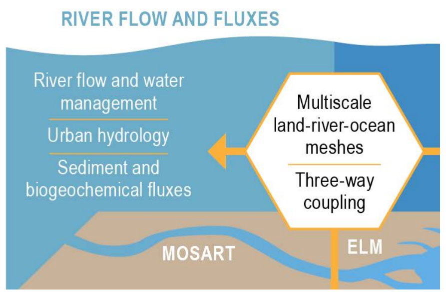
Without stream burning

With stream burning (Liao, et al. 20

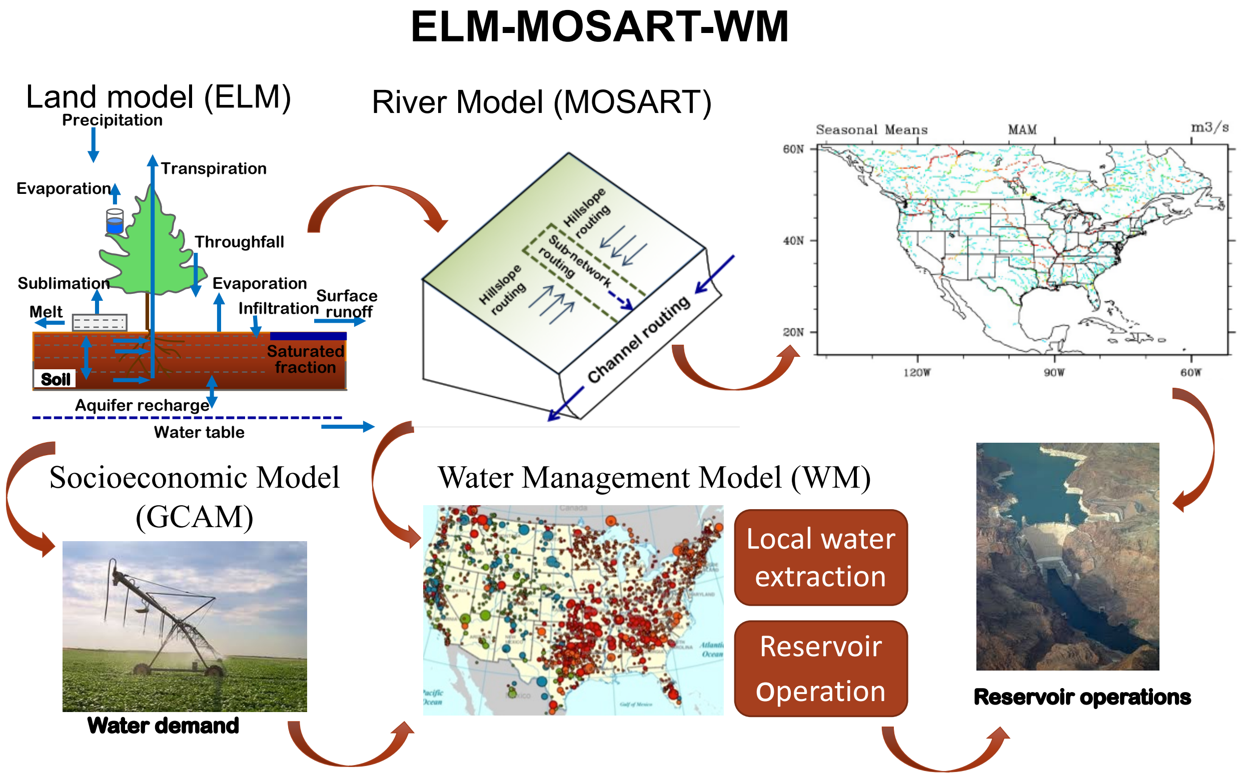


Poster: *A hexagonal mesh-based routing method for land surface and hydrological models* (Liao, PS2-Land_River_&_Energy)

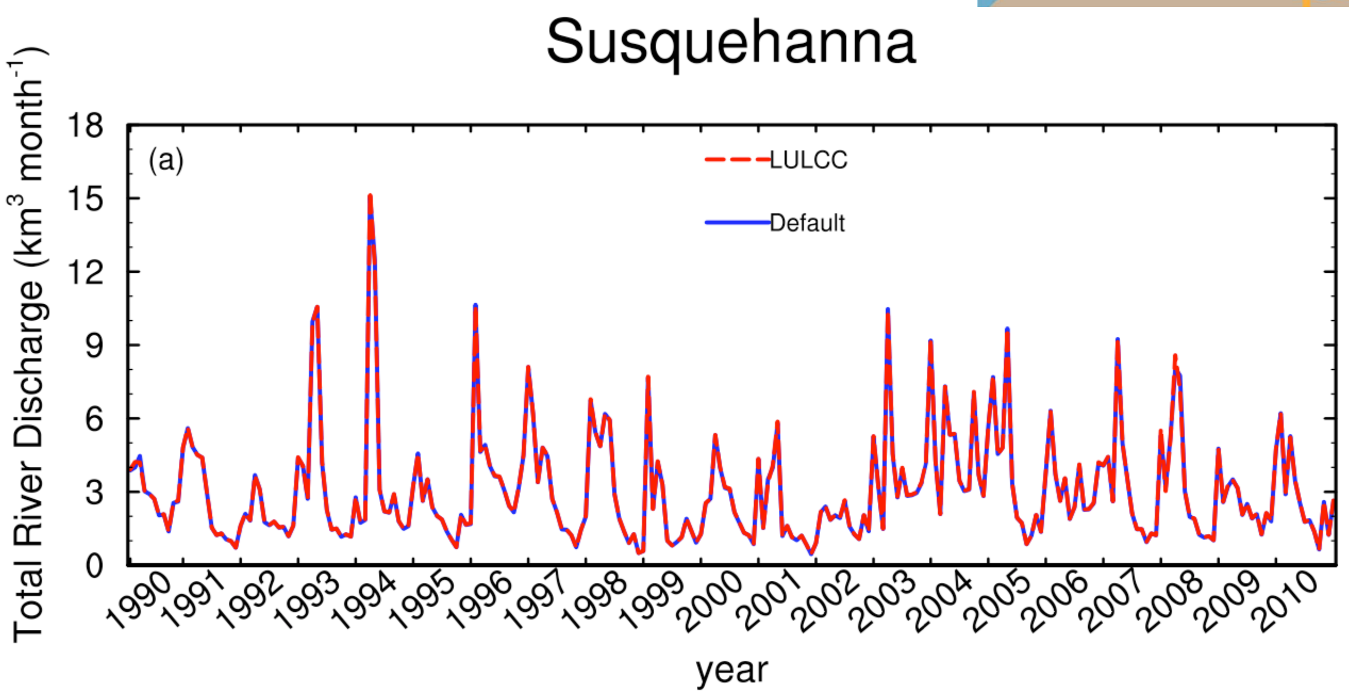
Water and sediment discharge on an unstructured mesh

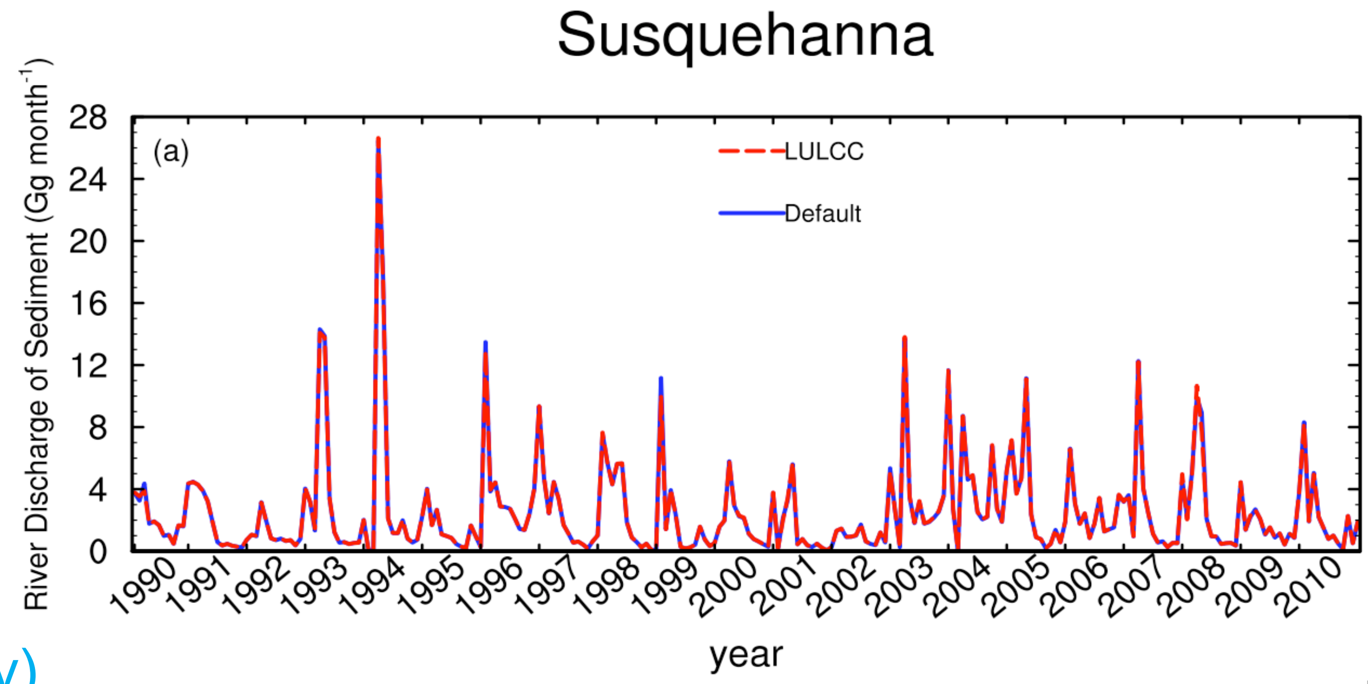


Simulated river flow and fluxes of the Susquehanna watershed using the ELM-MOSART-WM framework – now configured on an unstructured mesh



Li et al., 2013, 2015; Voisin et al., 2013a, b; Li et al., in review

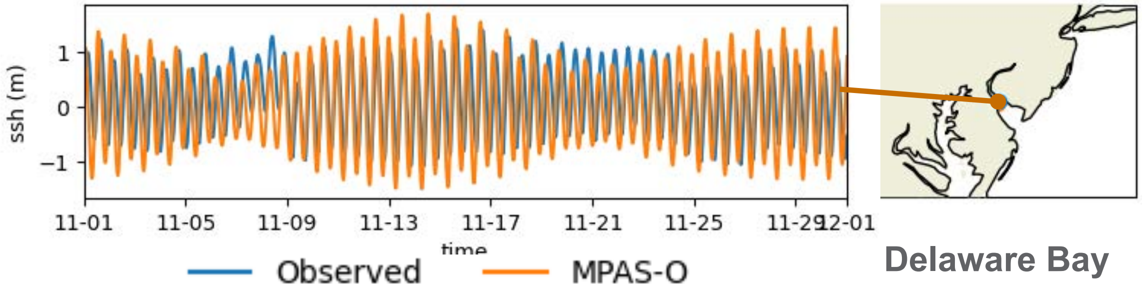




Poster: *Simulating river processes in a coupled Earth system* (Zhou, PS2-Land_River_&_Energy)

Zeli Tan

Estuary Dynamics: Global Tidal Modeling in E3SM



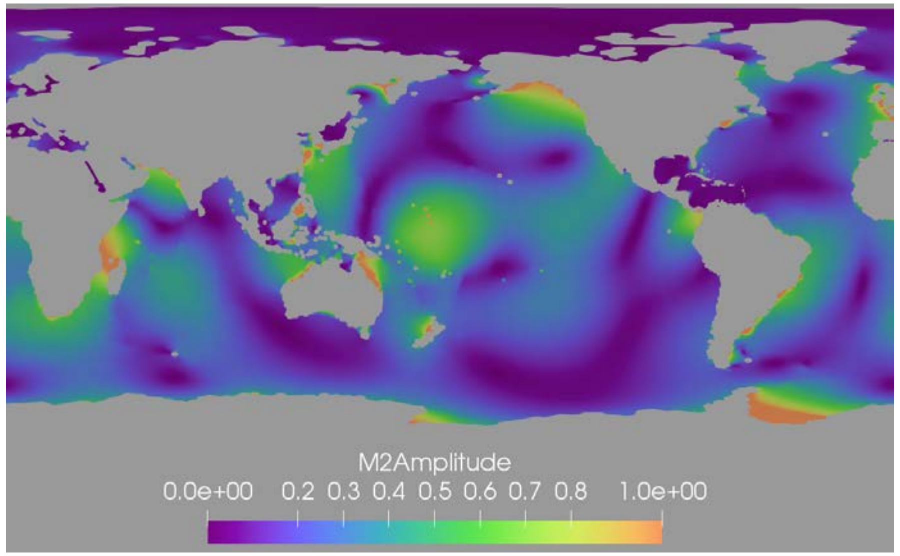
Delaware Bay

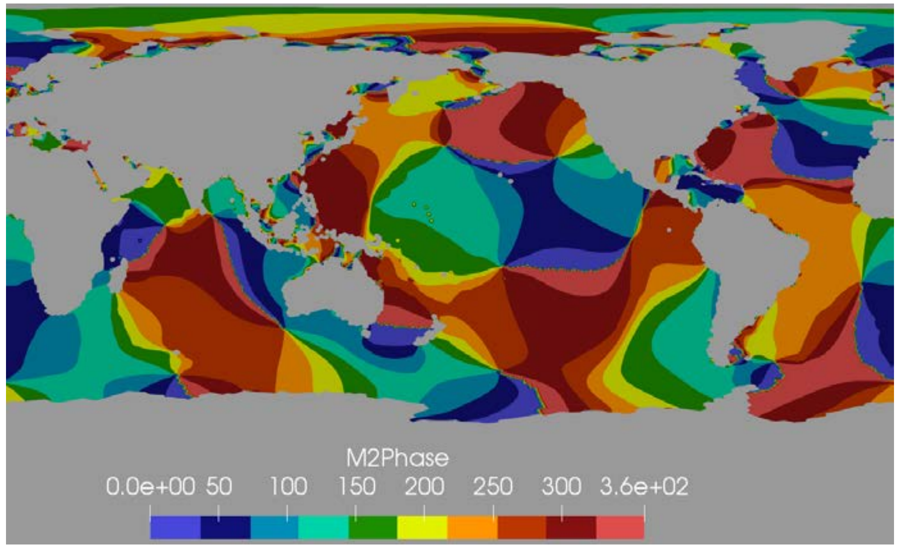
- Eight tidal constituents are now in MPAS-Ocean:

  M2, S2, N2, K2, K1, O1, Q1 and P1

- We are now making three important changes to MPAS-Ocean to improve the accuracy of the tides:
  - self-attraction and loading (SAL)
  - refined bottom drag
  - topographic wave drag
- There are two phases of tidal development in MPAS:
  - short-term (months-long) barotropic simulations
  - fully coupled climatic baroclinic simulations in E3SM, including sea ice, atmospheric and land coupling
- Simulating tides on a range of meshes ranging from 1-10km for the barotropic model to 14-60km for regionally- and bathymetrically-refined meshes

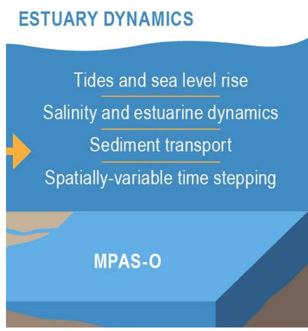
Talk by Brian Arbic and Joannes Westerink, Breakout D4S2-BR#4
Thursday,1:05 pm ET



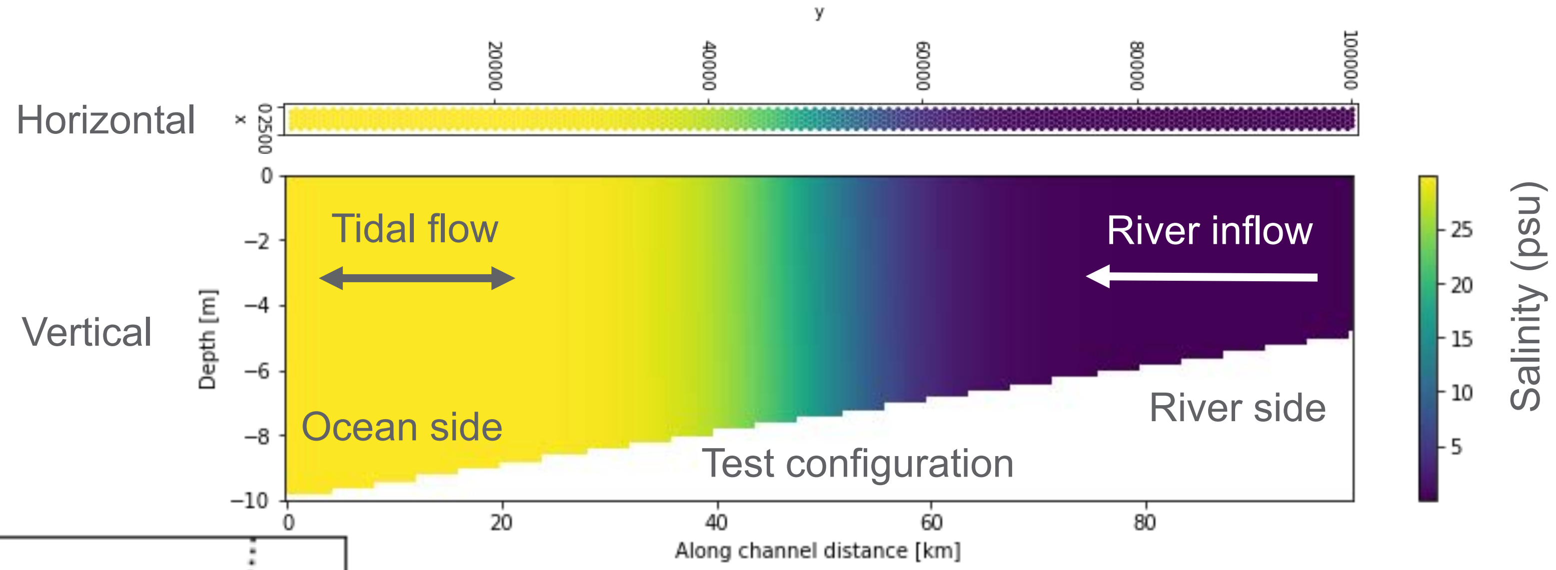


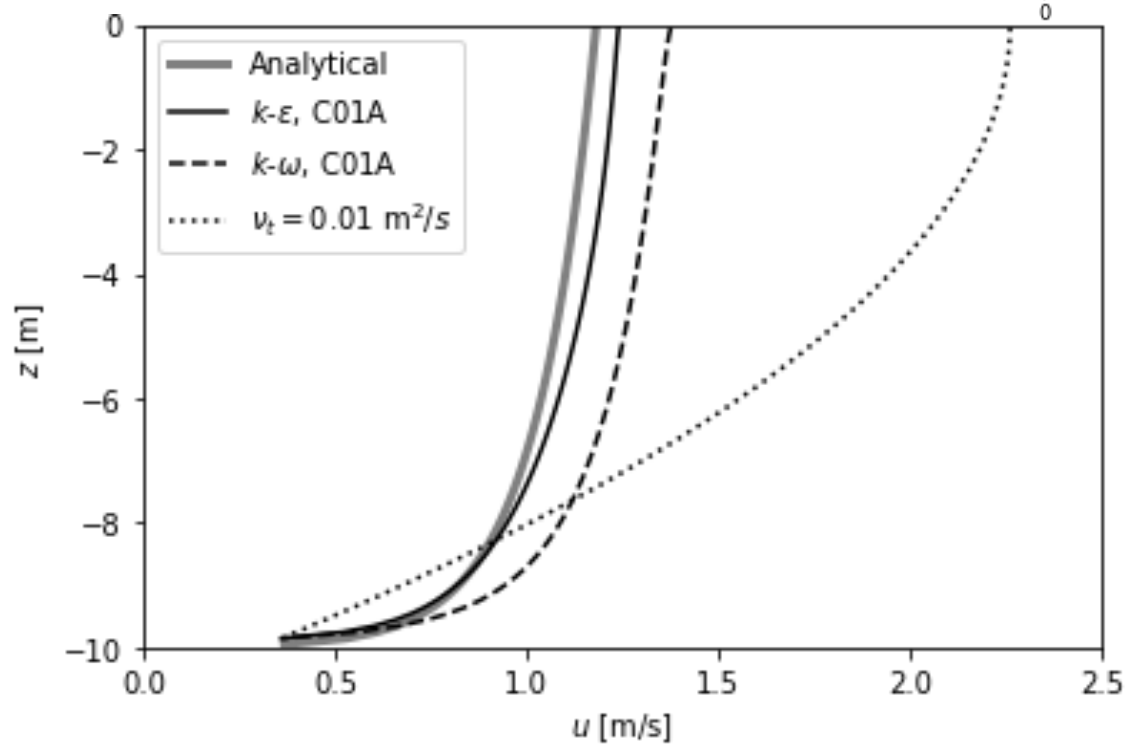
Example of the M2 Tide in MPAS-Ocean

Andrew Roberts, Brian Arbic, Kristin Barton, Stephen Brus, Giacomo Capodaglio, Nairita Pal, Mark Petersen, Joannes Westerink, Damrongsak Wirasae



Estuary Dynamics: Salinity





Single column simulation of GOTM in MPAS-O showing analytical solution compared with 2 turbulence closures (ε and ω) along with a constant viscosity simulation (ν_t).

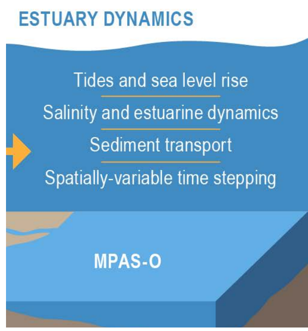
We must correctly model the balance between tidal forcing and river discharge to accurately capture the salinity front

- **Current work:** Implementing General Ocean Turbulence Model (GOTM) in MPAS-Ocean
- **Future work:** Realistic scenario in the Delaware Basin with tides and river forcing

Poster: *Implementation of turbulence and sediment transport models in MPAS-Ocean* (Cao & Li, PS1-Ocean_Coastal)

LeAnn Conlon, Qing Li

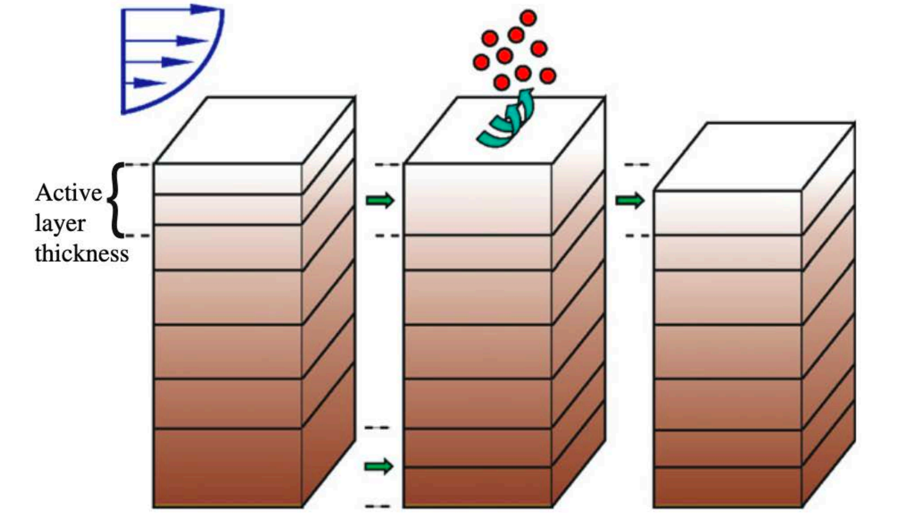
Estuary Dynamics: Sediment Transport



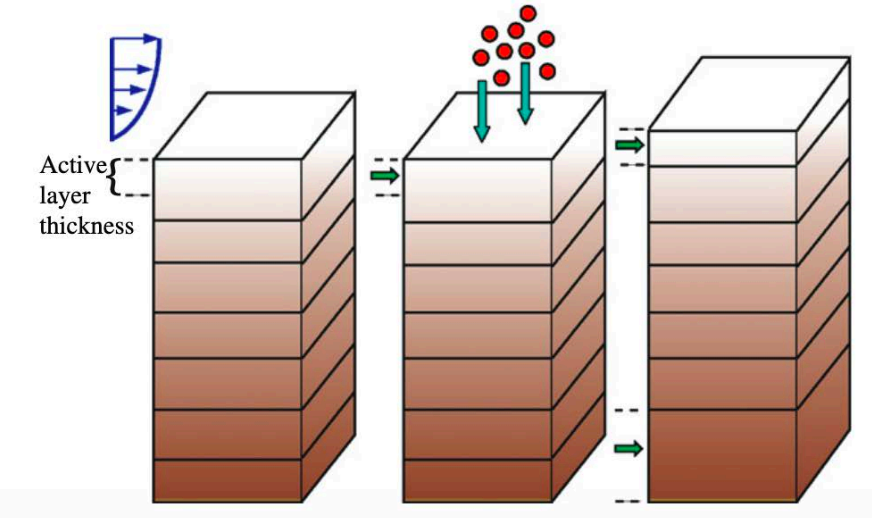
- Sediment transport affects
  - estuarine turbidity
  - phytoplankton productivity
  - nutrient cycling
- **Current work**: advection and diffusion of sediment in an idealized case of MPAS-O (based on Warner et al. 2008)
- **Future work**: erosion and deposition, changing coastline morphology, etc.

Poster: *Implementation of turbulence and sediment transport models in MPAS-Ocean* (Cao & Li, PS1-Ocean_Coastal)

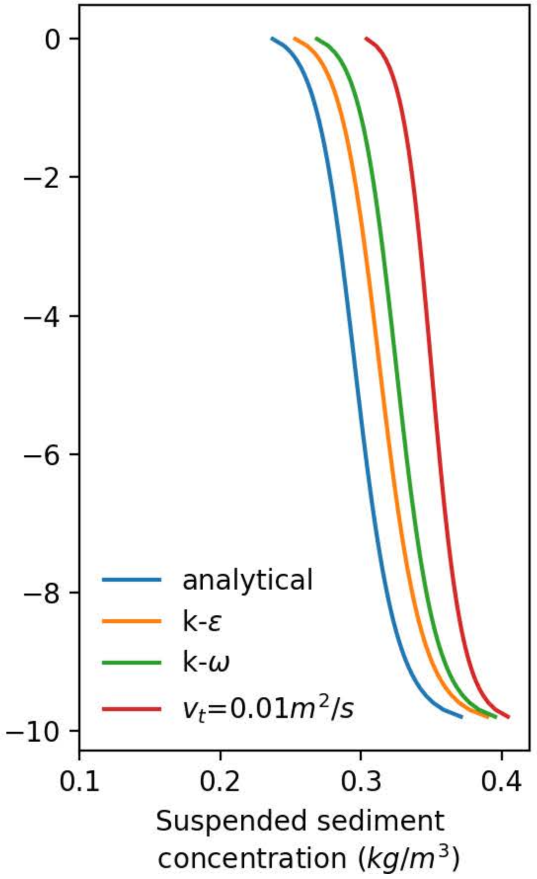
Vertical structure of bed model
(Warner et al. 2008)



Erosion: sediment is eroded from surface; layer disappears if a specified amount is removed



Deposition: Create new layer if deposition is greater than specified amount.

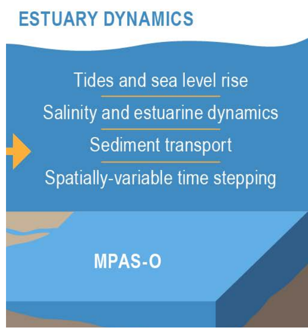


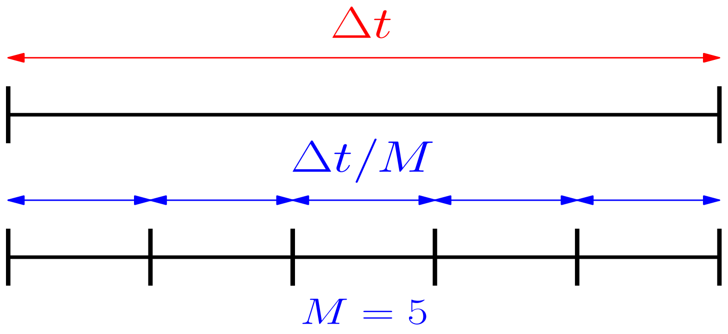
Single column simulation forced by a constant pressure gradient, balanced by bottom drag

Warner et al. 2008 Development of a three-dimensional, regional, coupled wave, current, and sediment-transport model. Computers & Geosciences 34 (2008) 1284–1306

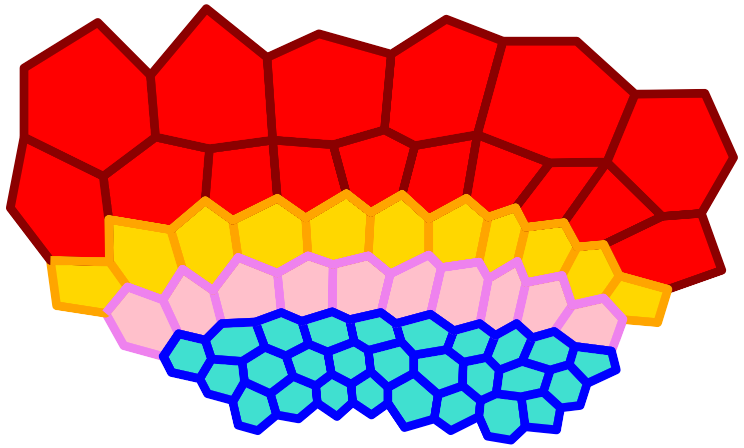
LeAnn Conlon, Zhendong Cao

Estuary Dynamics: Local time-stepping for fast and efficient multi-resolution simulation of global to coastal ocean





Δt is the coarse time-step.
Δt/M is the fine time-step.



Red: low resolution cells.
Advance with *coarse* time-step.
Yellow: interface layer 2 cells.
Advance with *coarse* time-step.
Pink: interface layer 1 cells.
Advance with *coarse* time-step, interpolate to fine time-step.
Blue: high resolution cells.
Advance with *fine* time-step.

Local time stepping scheme

1. Predict interface: advance the solution in pink and yellow cells with the coarse time-step, then interpolate to intermediate time steps in pink cells.
2. Advance coarse and fine solution on the red and blue cells.
3. Correct interface: update the solution in pink and yellow cells using the coarse time-step.

Progress to date

The local time stepping scheme has been implemented and tested in the shallow water core of MPAS. The number of interface layers is extensible.

Next steps

- Obtain quantitative results for the CPU time reduction from using a coarse time-step in the low resolution region
- Integrate the algorithm within the MPAS ocean core

Reference: *Conservative explicit local time-stepping schemes for the shallow water equations,* Hoang et al., J. Comp. Phys. 2019.

Poster: *Local time stepping schemes for global to coastal simulations in MPAS-Ocean* (Capodaglio, PS1-Ocean_Coastal)

Mark Petersen, Giacomo Capodaglio

Numerical experiment plans

Stand-alone simulations to address ESMD questions covering two five-year time periods

Coupled simulations will run at low resolution globally (30 to 60km) with enhanced resolution in US coastal and mid-Atlantic region (1 to 10km). Simulations will cover the two five-year time periods and a century-long simulation.

NERSC ERCAP proposal includes both Stand-alone and Coupled simulations:

- Global tidal modeling
- River flow and BGC fluxes modeling
- River-land coupling simulations
- River-Ocean coupling simulations
- Land-River coupling simulations

NERSC computing resources requested:
7M hours + 7T storage (Land/River)
41.25M hours + 156T storage (Ocean)

	Process evaluations								Simulation length		
	Land-river			*Ocean*				*Coupled*	*Hypoxia*	*Floods*	*Historical & Future*
Science Questions	*Data*	*WM*	*UH*	*Data*	*Mixing*	*Tides*	*SLR*	*Tuned*	*1960-1965*	*2010-2015*	*1960-2060*
CC1: Flooding **CC2: Hypoxia**								X	X	X	
ESMD1: Flooding **ESMD2: Salinity** **ESMD3: Sediment**								X			X
Inland ESMD1a *Riverine ESMD2a* *Watershed ESMD3a*		X	X	X					X	X	
Nearshore ESMD1b *Estuarine ESMD2b* *Estuarine ESMD3b*	X				X	X	X		X	X	

WM is water management, UH is urban hydrology, green indicates land-river simulations, blue indicates coastal ocean simulations, and light blue indicates coupled land-river-ocean simulation.

ICoM

Cross-cutting hypoxia modeling collaboration

Hypoxia modeling partners

Virginia Institute of Marine Science
Marjy Friedrichs

Rutgers University
John Wilkin

Pennsylvania State University
Raymond G. Najjar

- Compare ICoM's terrestrial runoff and ocean boundary conditions to those of ChesROMS-ECB for the Chesapeake and Delaware estuaries
  - Terrestrial runoff: water, sediment, carbon, nutrients
  - Ocean: tides, salinity, sea level
- Force ChesROMS-ECB with ICoM boundary conditions in historical and future conditions
  - How do the frequency and intensity of hypoxia in the two estuaries respond to changes in climate, coastal development and land use?
- Analyze simulations of ICoM's hypoxia models to understand when/where/why their skills differ

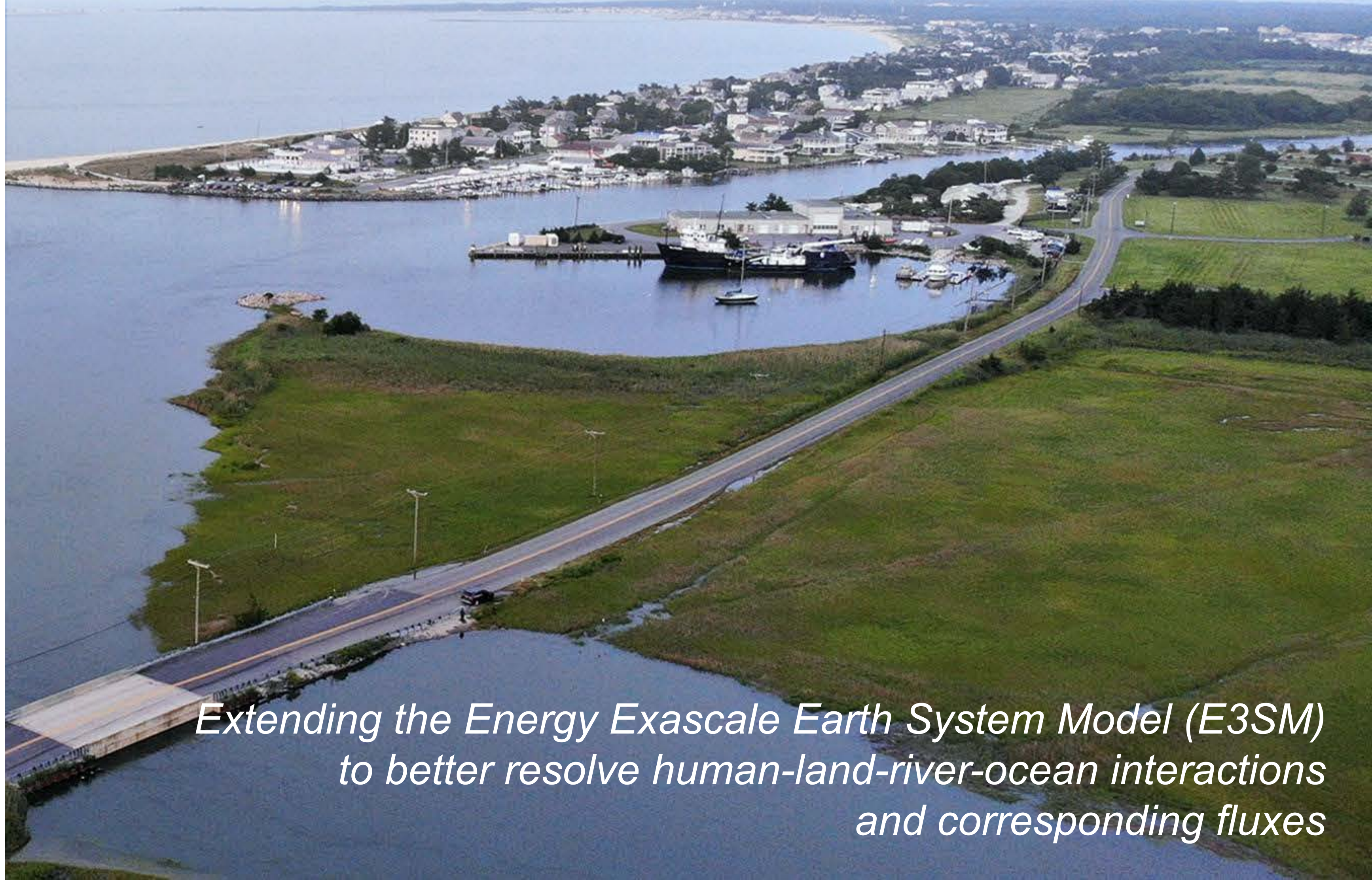
Cross-cutting atmosphere-ocean coupled system talk:
Creation of an SST variability metric for E3SM
(LeAnn Conlon, Water Cycle Breakout #1, Thursday 11:20 am ET)

Zeli Tan, Elizabeth Hunke

Planned Outcomes:

- Land-river-ocean coupling with resolved estuaries in E3SM, allowing simulation of flows, fluxes, and coupled processes related to water transport at the terrestrial aquatic interface
- Multi-decadal simulation of coupled coastal climate change hazards in E3SM
- Understanding drivers, sensitivities, and feedbacks of flooding, nutrient, and sediment transport within an integrated coastal climate model

Thank you



Extending the Energy Exascale Earth System Model (E3SM) to better resolve human-land-river-ocean interactions and corresponding fluxes